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Impact of Wake Dispersion on Axial Compressor Peformance

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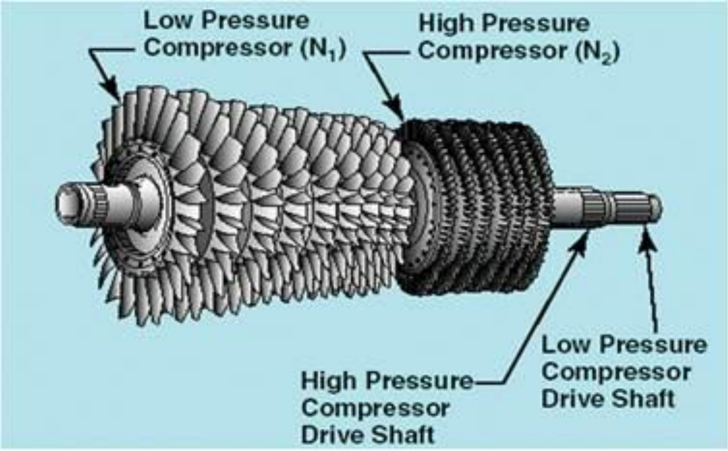
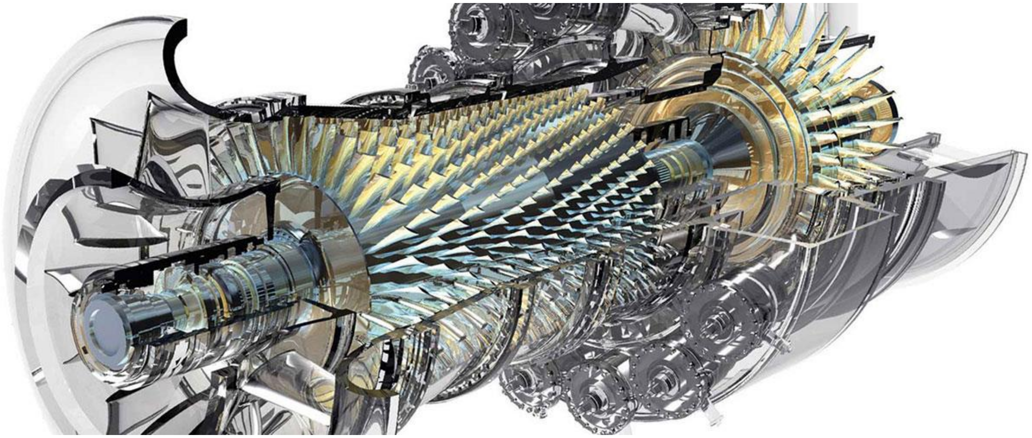
Background

- Needs to advance current understanding of flow physics in modern highly-loaded compact compressor stages.
- Needs to develop prediction tools based on higher-fidelity CFD tools (DES, LES, DNS, etc.).

Changes in multi-stage compressor design



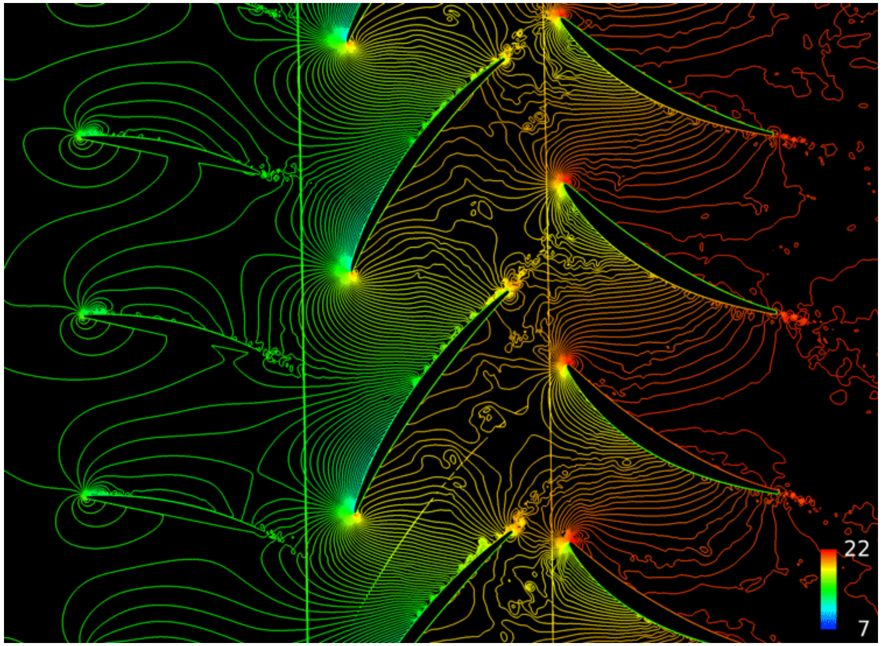


Less spacing between blade rows.
Higher loading per blade rows.

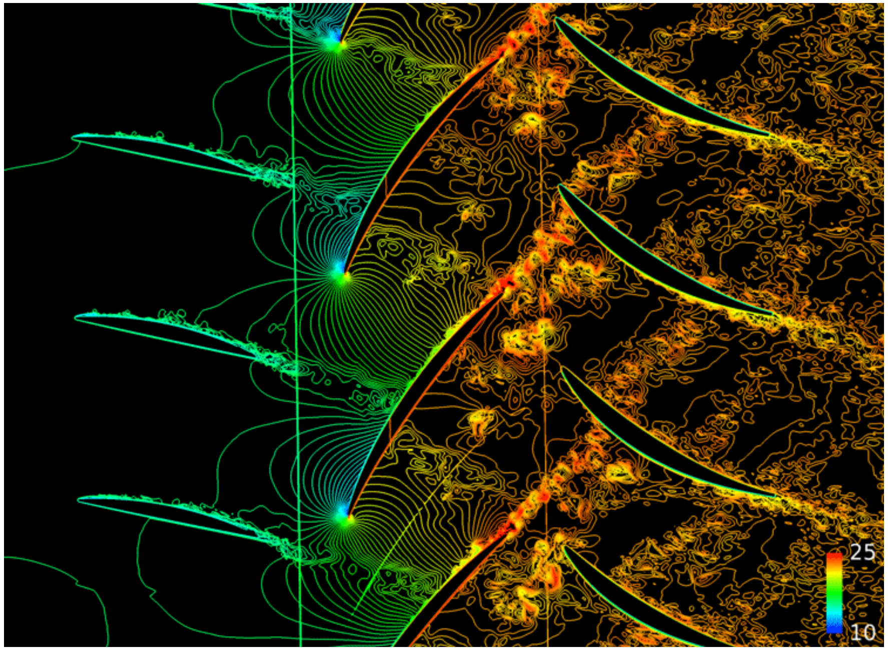
Main aerodynamic performance effects of closely-coupled compressor blade rows

1. Upstream influence of pressure field of the downstream blade row.

2. Effects of wake dispersion on the downstream blade row.



Ps



Pt

Earlier investigations of the wake dispersion on compressor performance

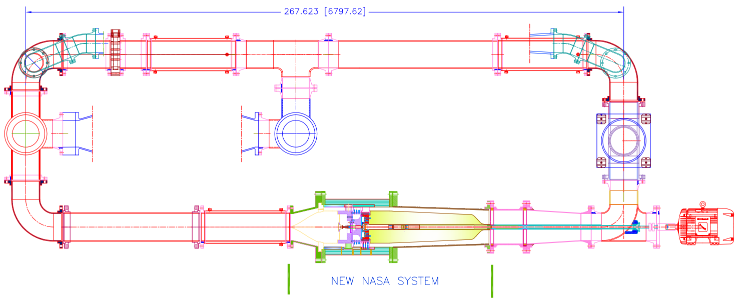
L. H. Smith (1966) : 1.2 points efficiency gain when axial spacing
is reduced from 37 to 7 percent of chord.

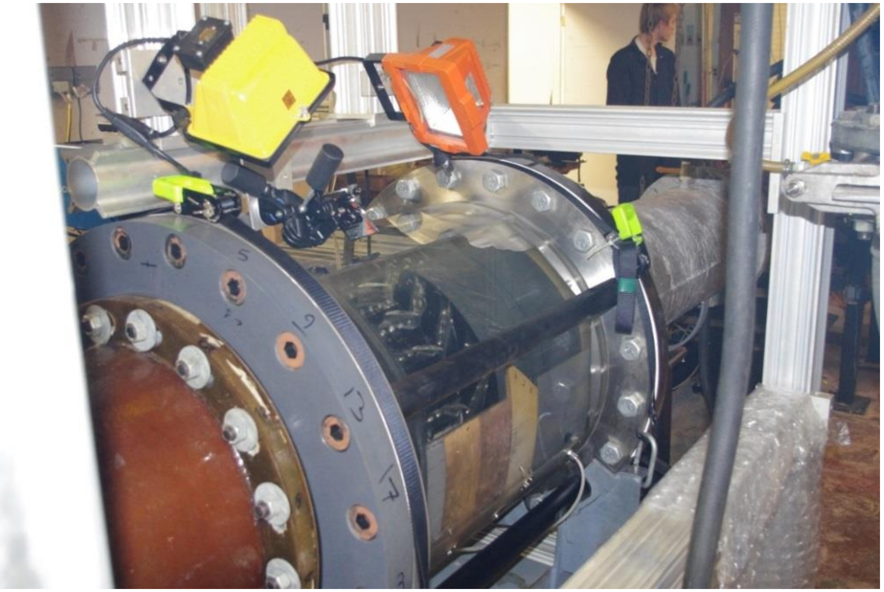
0.68 points due to upstream pressure effects.
0.52 points due to wake recovery.

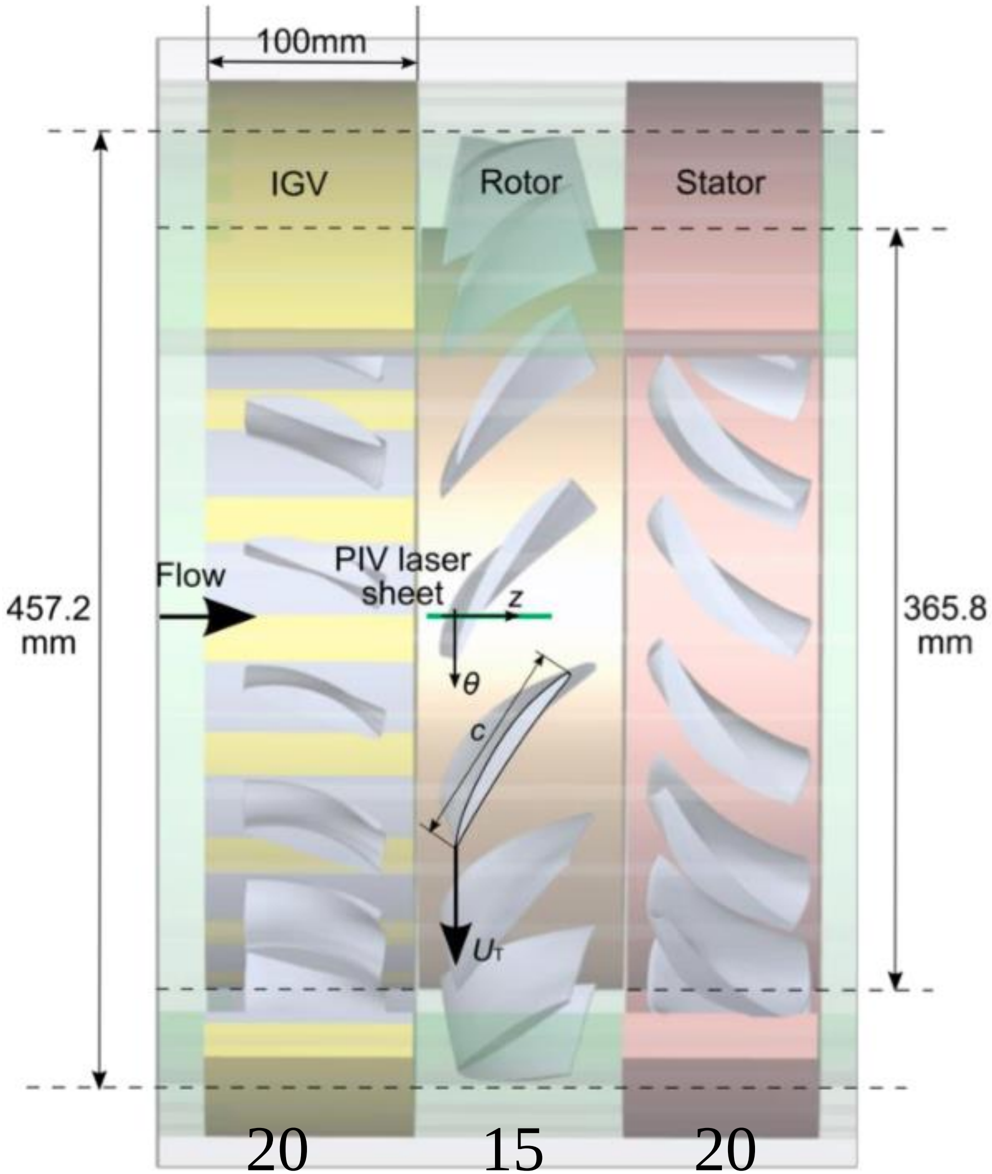
Objectives

- Investigate effects of wake dispersion on the compressor performance.
- Conducted in one and a half stage axial compressor with two spacing between rotor and stator (112 % and 29% of rotor axial chord at mid-span).
- LES was applied for the flow simulation.

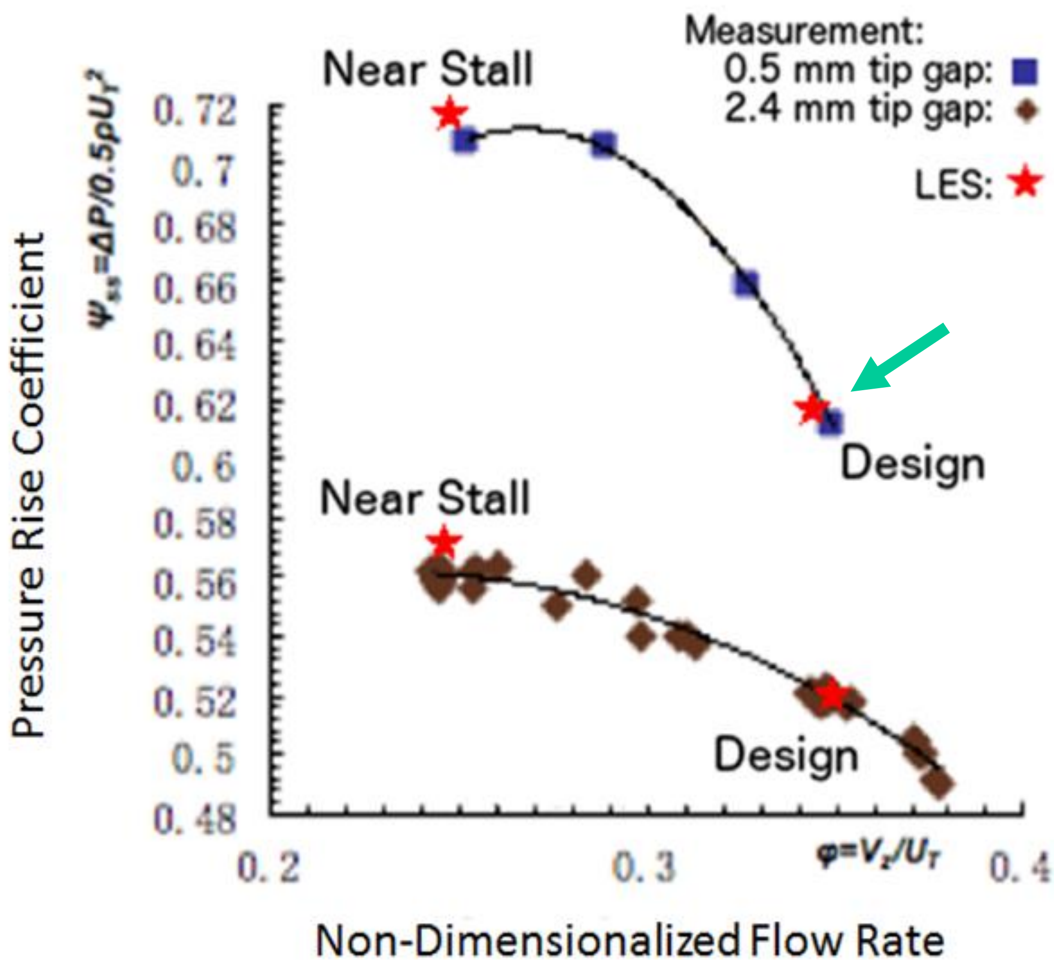
Axial compressor stage at JHU test facility







Pressure rise characteristics of the original compressor stage



Previous LES

- Hah et al.[2015]
- Hah[2017].

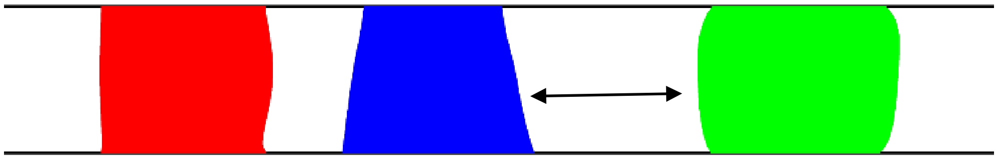
Applied LES procedure

- 3^{rd}-order scheme for convection terms.
- 2^{nd}-order central differencing for diffusion terms.
- Sub-iteration at each time step.
- Dynamic model for sub grid stress tensor.
- Multi-block I-grid, 1.2 billion nodes for 4-3-4 simulations with 60 radial nodes inside tip gap.

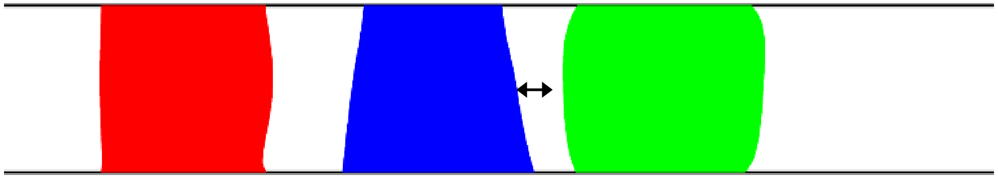
Test section and blade geometry

Casing Diameter (D) [mm]	**457.20**
Hub Diameter (d) [mm]	**365.76**
Rotor Diameter (D_R) [mm]	**455.92**
Rotor Blade Chord (c) [mm]	**102.60**
Rotor Blade Span (γ) [^{0}]	**45.08, 43.92**
Rotor Blade Stagger Angle (c_A) [mm]	**58.6**
Rotor Blade Axial Chord [mm]	**53.46**
Nominal Tip Clearance [mm]	**0.64 (0.62% of c), 1.8 (1.75%)**
Measured Tip Clearance (h) [mm]	**0.5 (0.49%), 2.4 (2.3%)**
Shaft Speed (Ω) [rad s^{-1}] {RPM}	**50.27 {480}**
Rotor Blade Tip Speed (U_T) [ms^{-1}]	**11.47**
Reynolds Number ($U_T\ c/\nu$)	**1.07 x 10^6**

Cross section of two configurations
(tip clearance of 0.5 mm, 0.8% rotor span)



112 % spacing

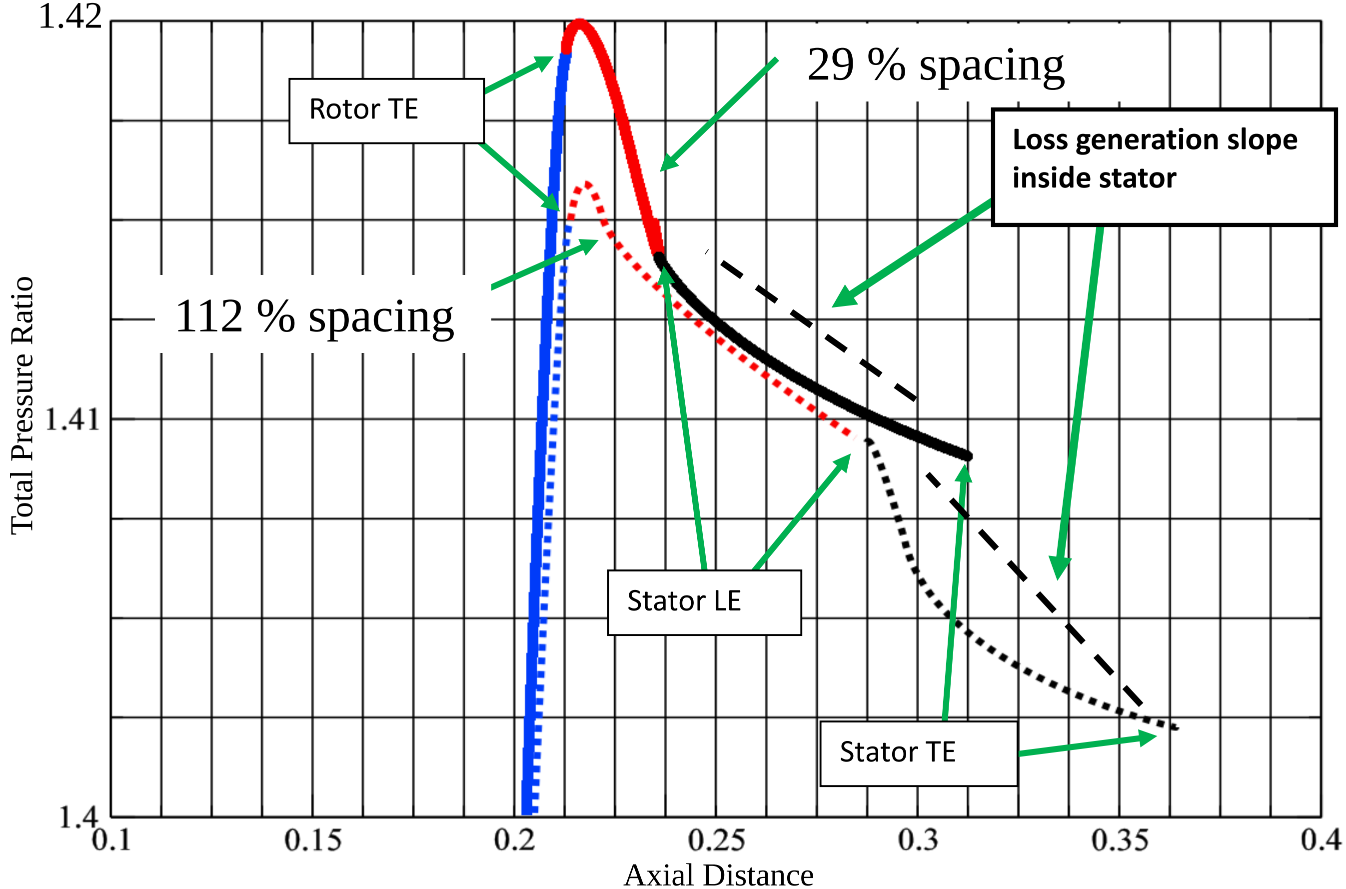


29 % spacing

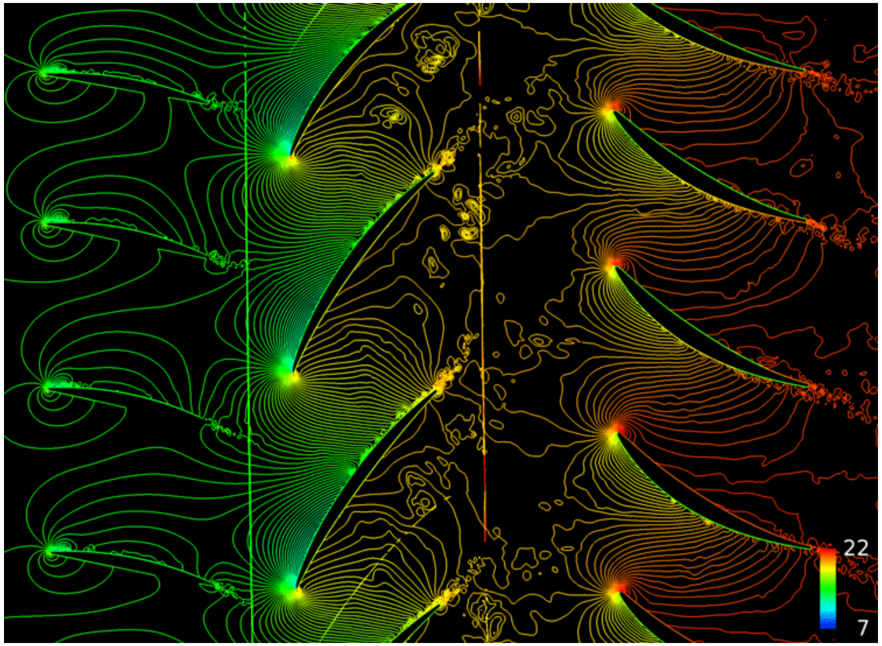
Calculated effects of axial spacing between rotor and stator on total pressure rise

1. Effects of non-uniform pressure field of stator on rotor performance.
2. Effects of rotor wake on stator performance (wake recovery and wake/stator interaction).

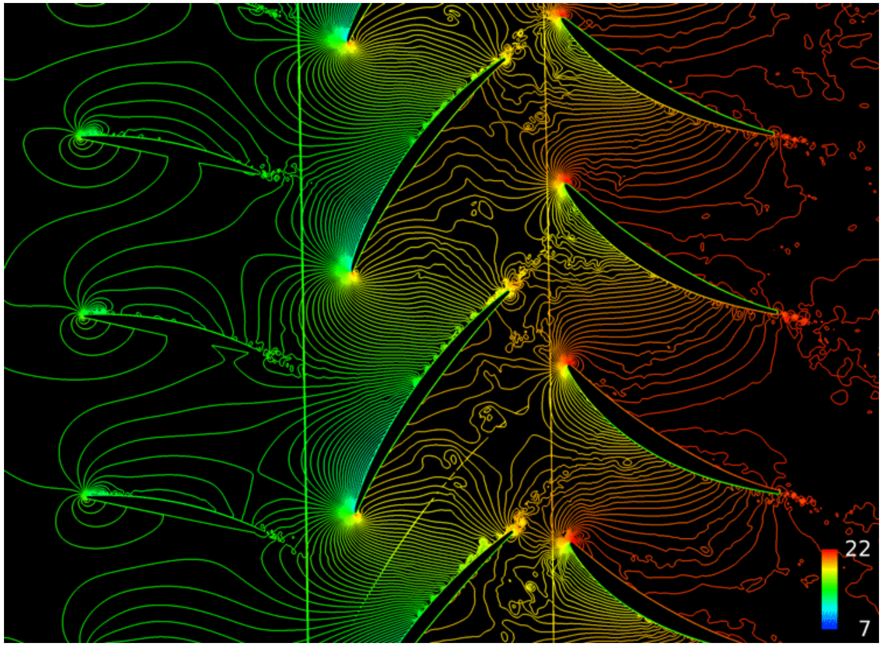
Absolute pressure rise from rotor LE to stator TE



Upstream effects of stator pressure field

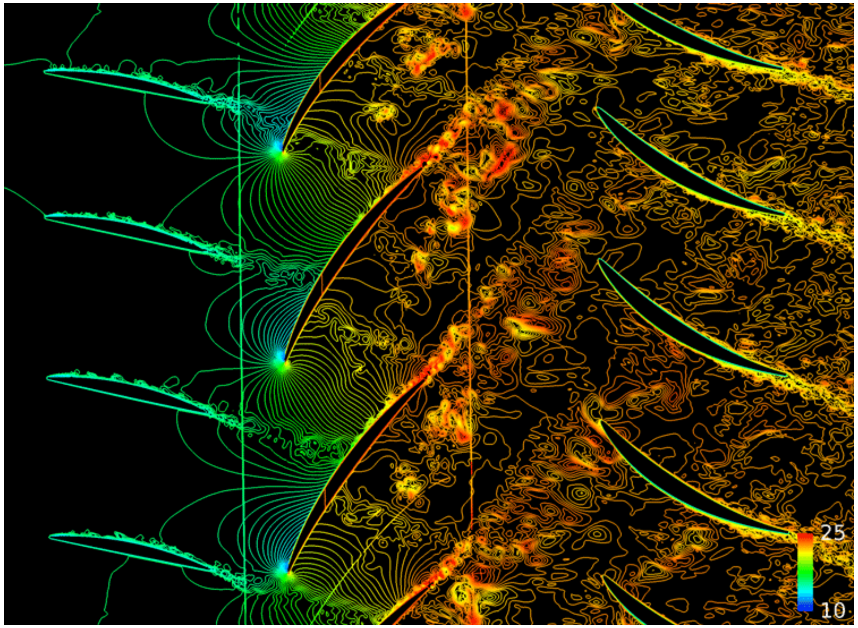


112 % spacing

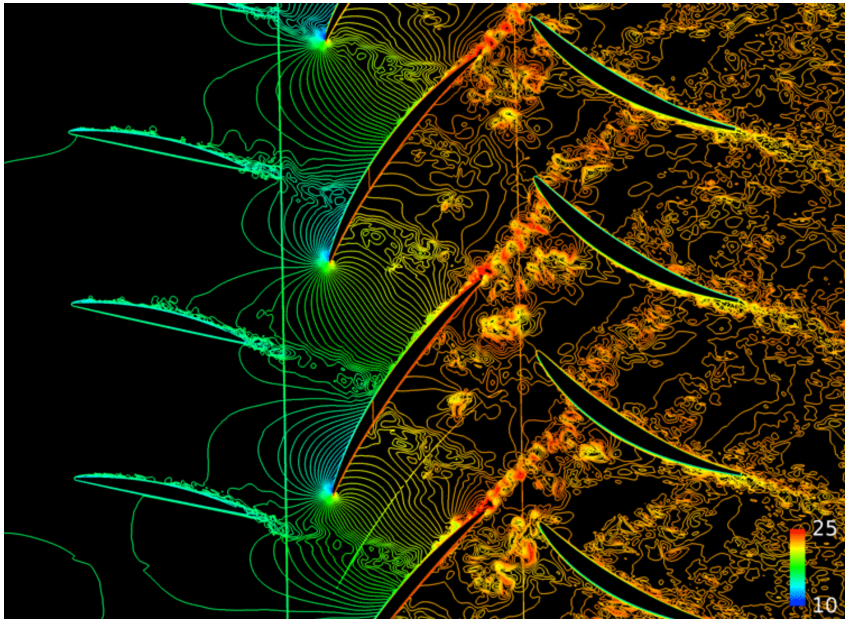


29 % spacing

Pt distribution due to wake dispersion

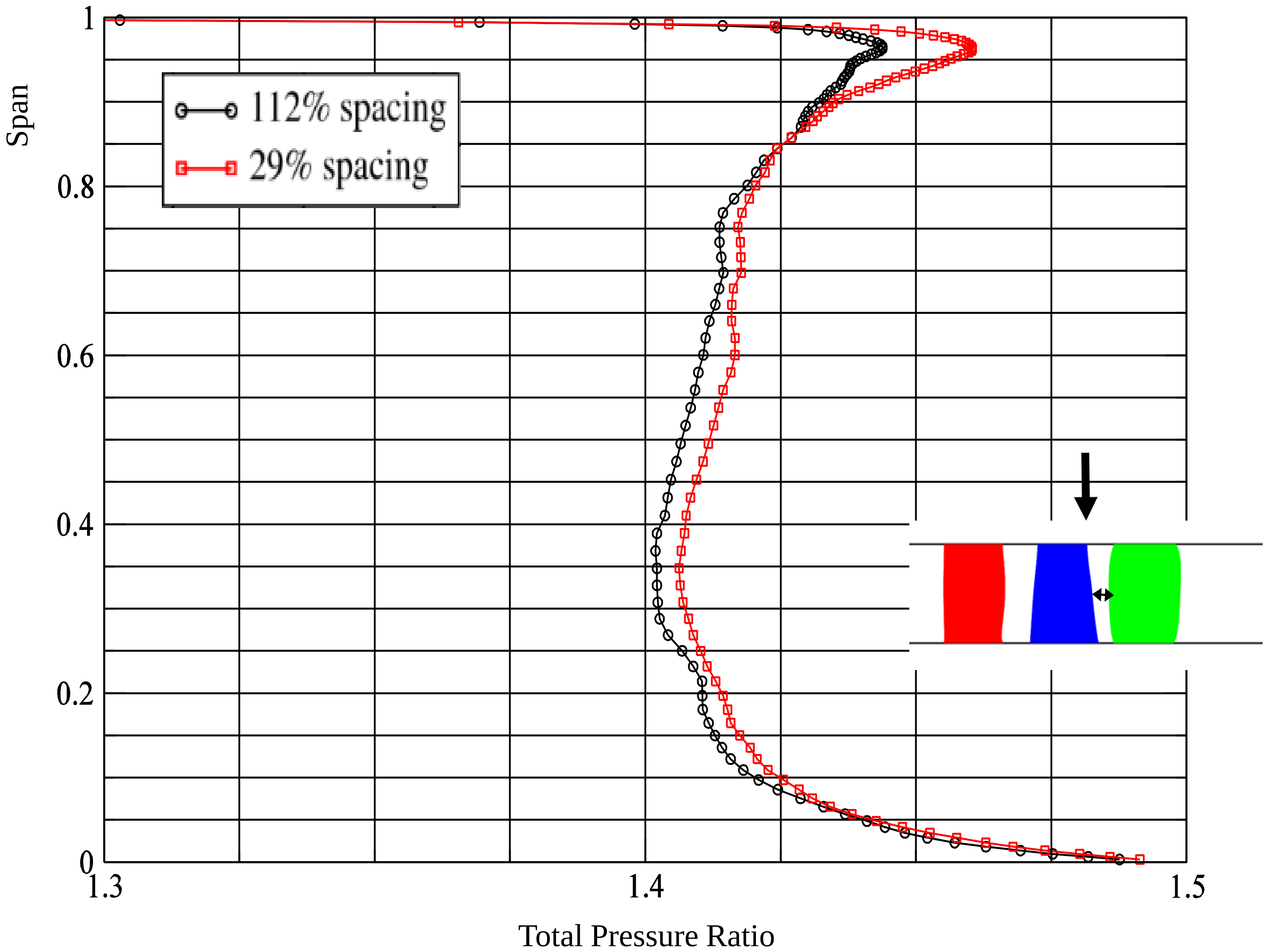


112 % spacing

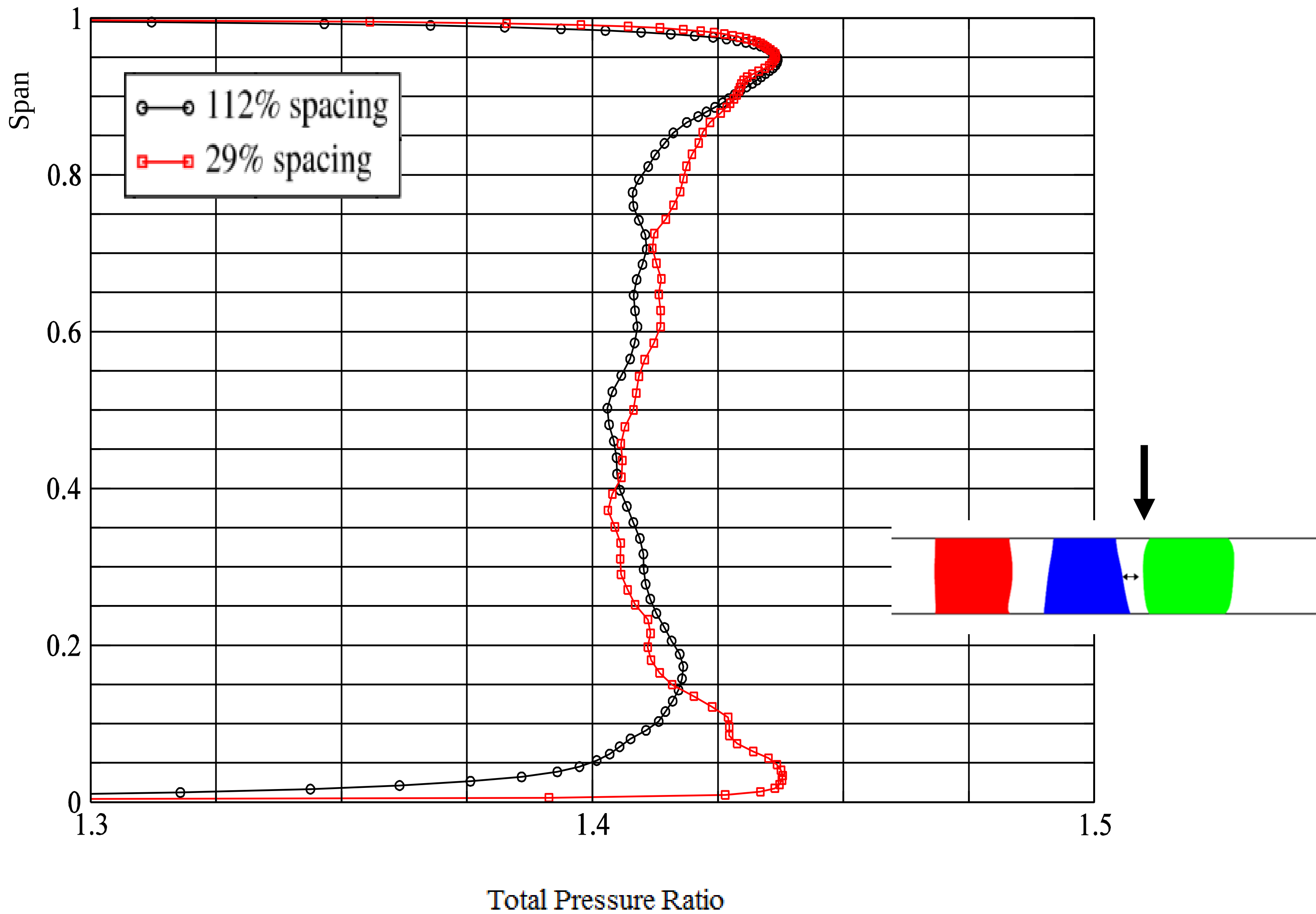


29 % spacing

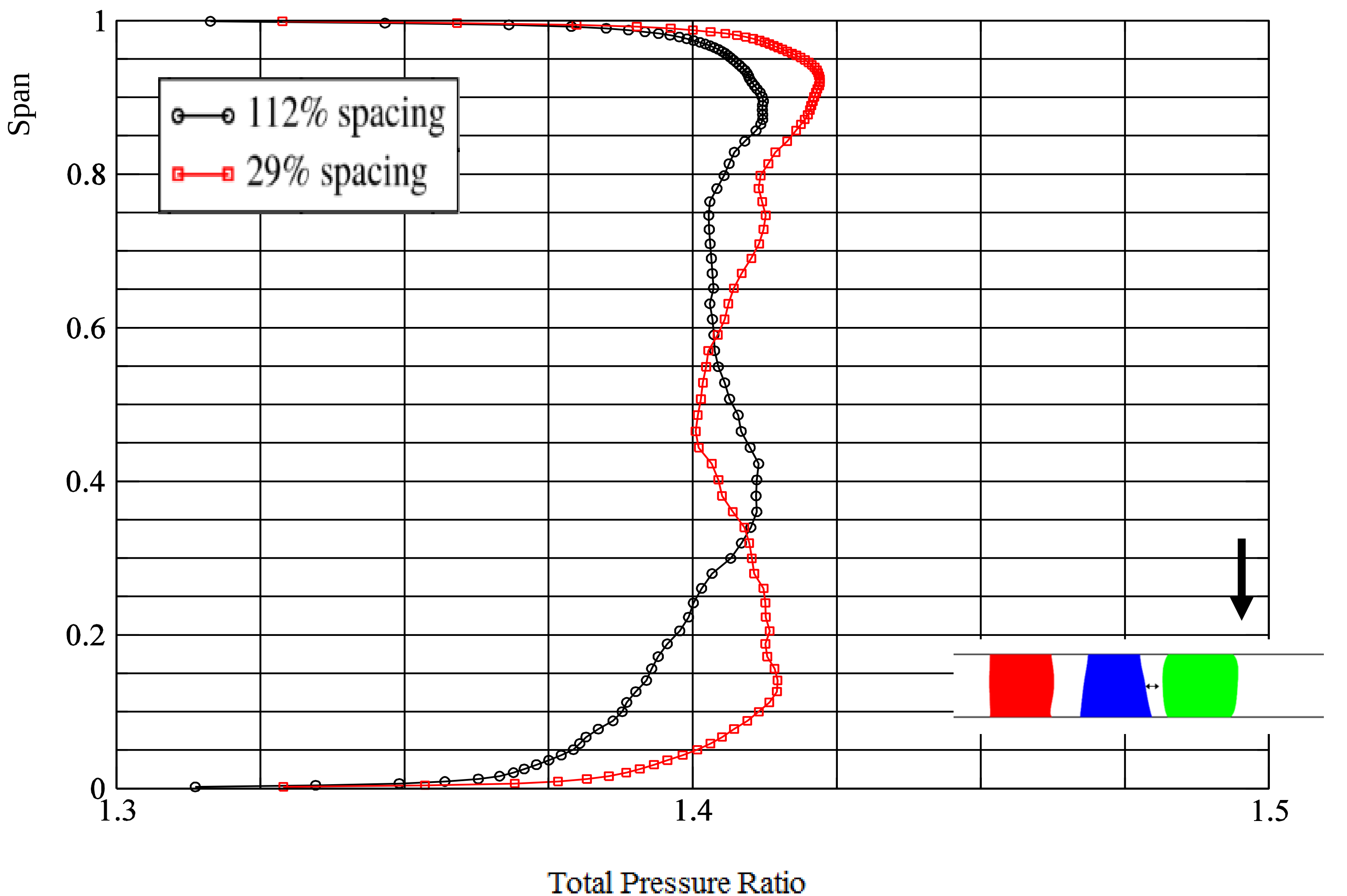
Pt distribution at rotor exit



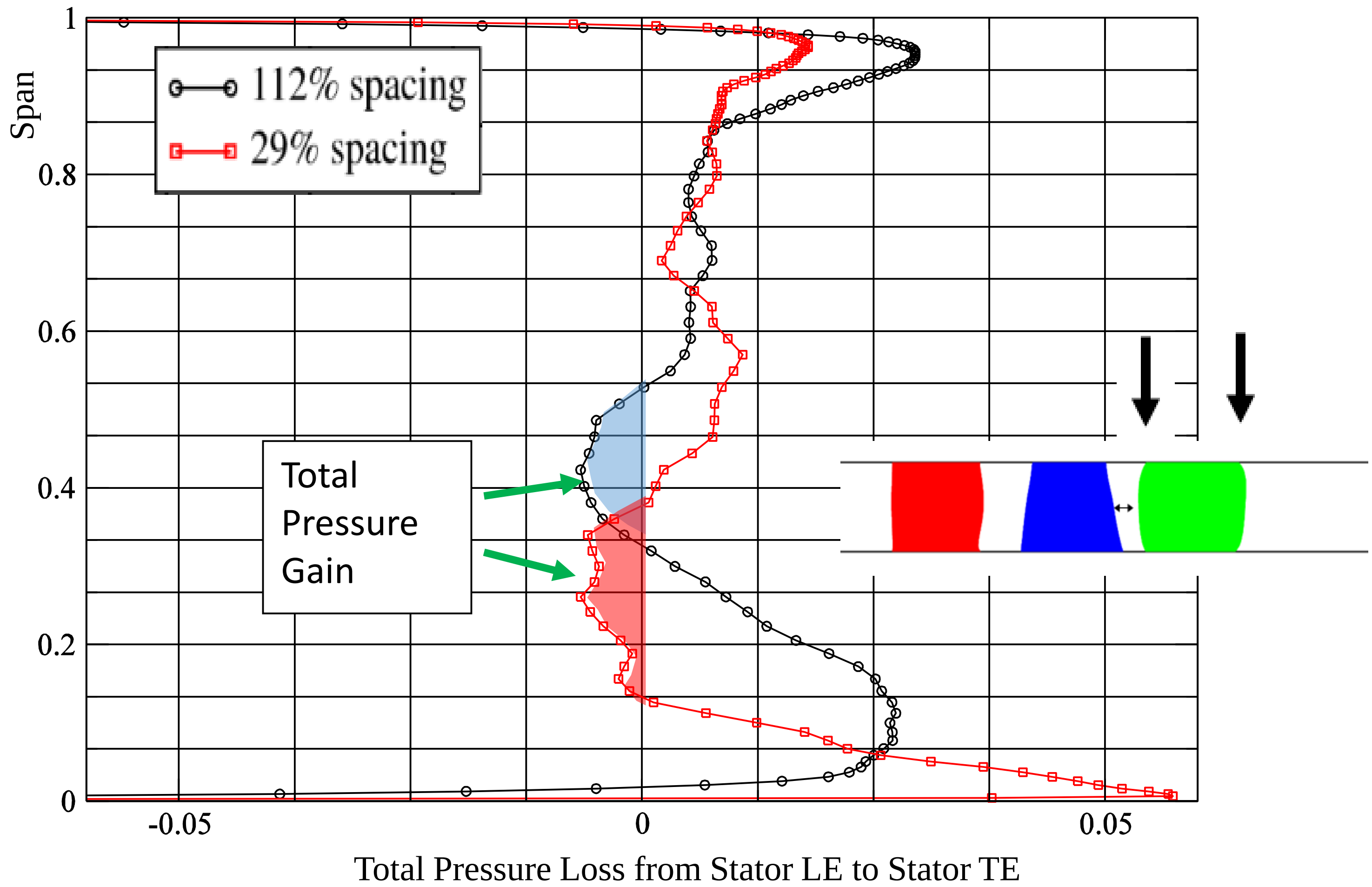
Pt distribution at stator LE



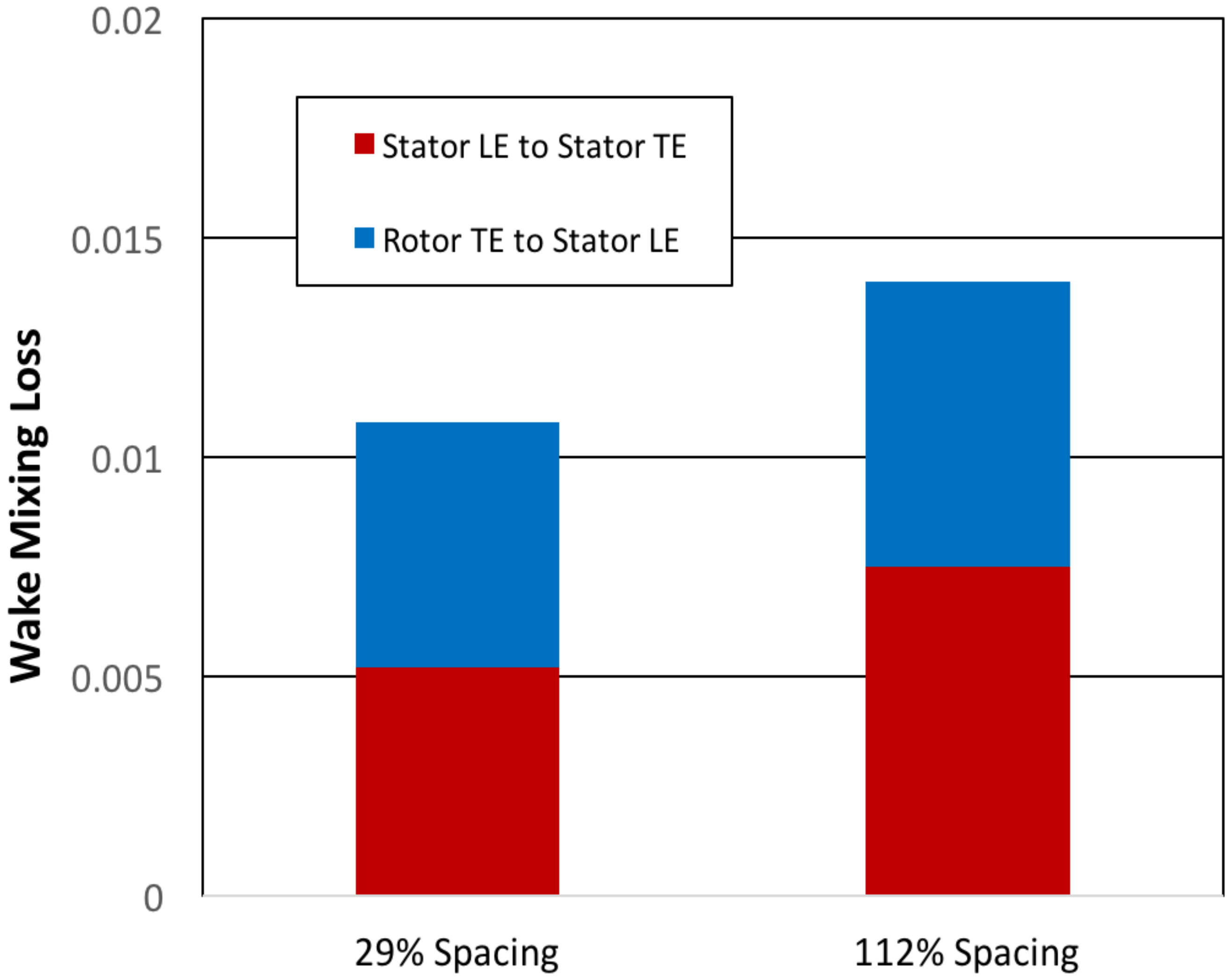
Pt distribution at stator TE



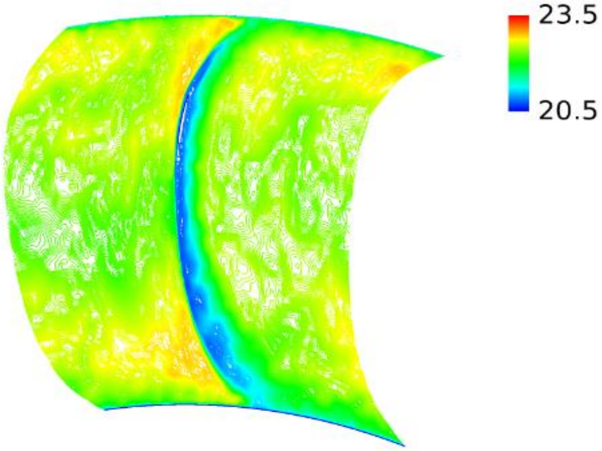
Pt loss from Stator LE to TE



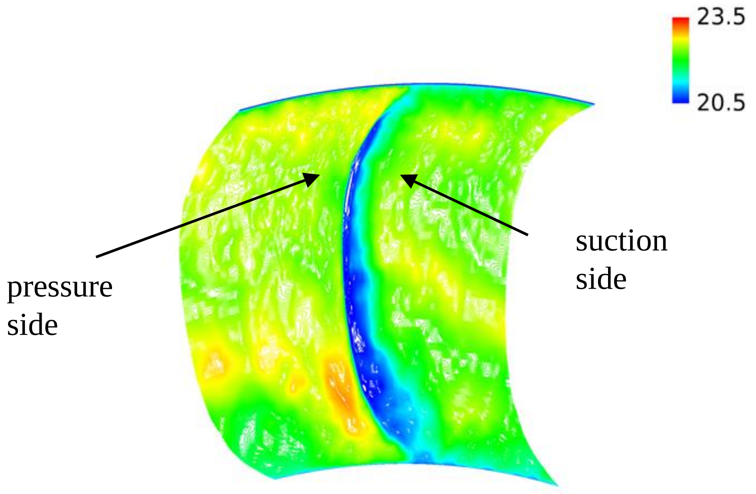
Breakdown of wake mixing loss from rotor TE to stator TE



Time-averaged Pt at stator TE

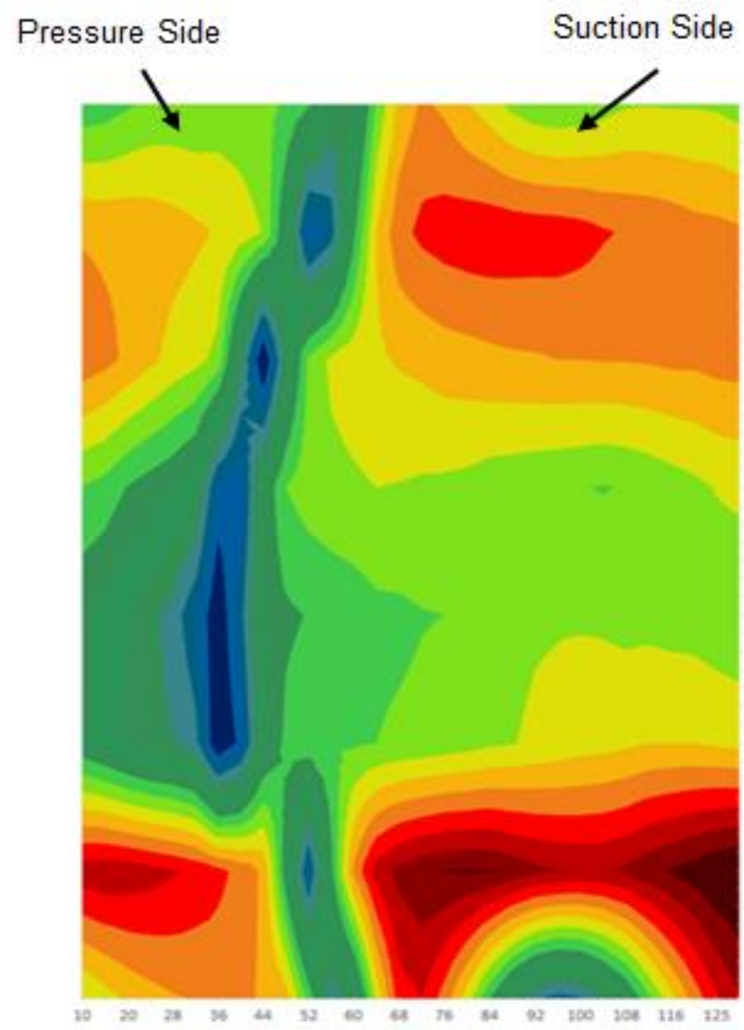


29 % spacing

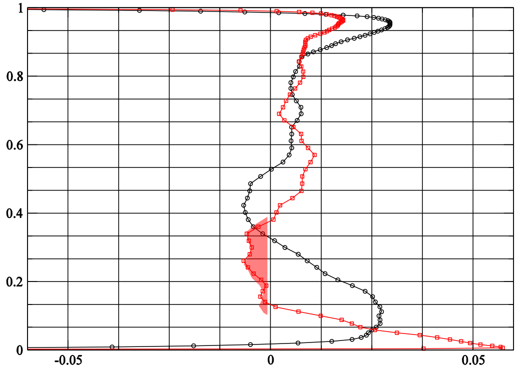


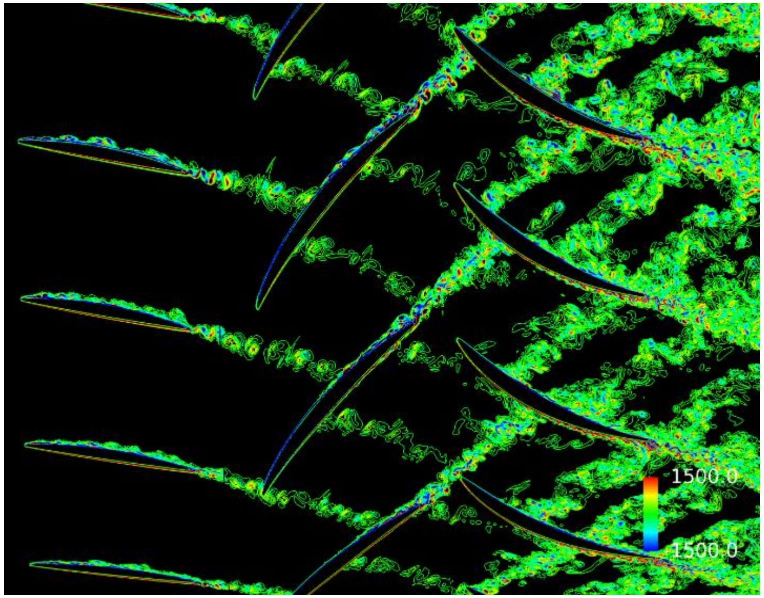
112 % spacing

Measured Pt at stator exit, 1&1/2 stage high speed compressor (Lurie and Breeze-Stringfellow[2015]

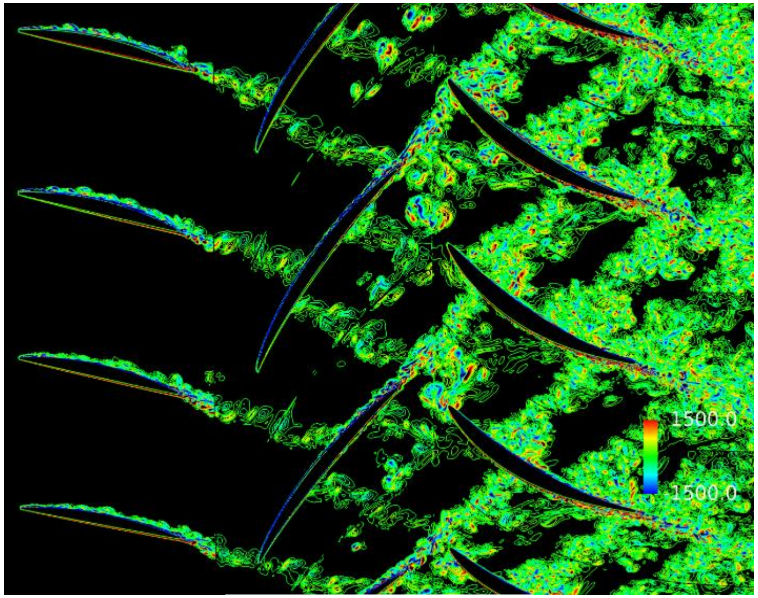


Instantaneous radial vorticity, 29% spacing





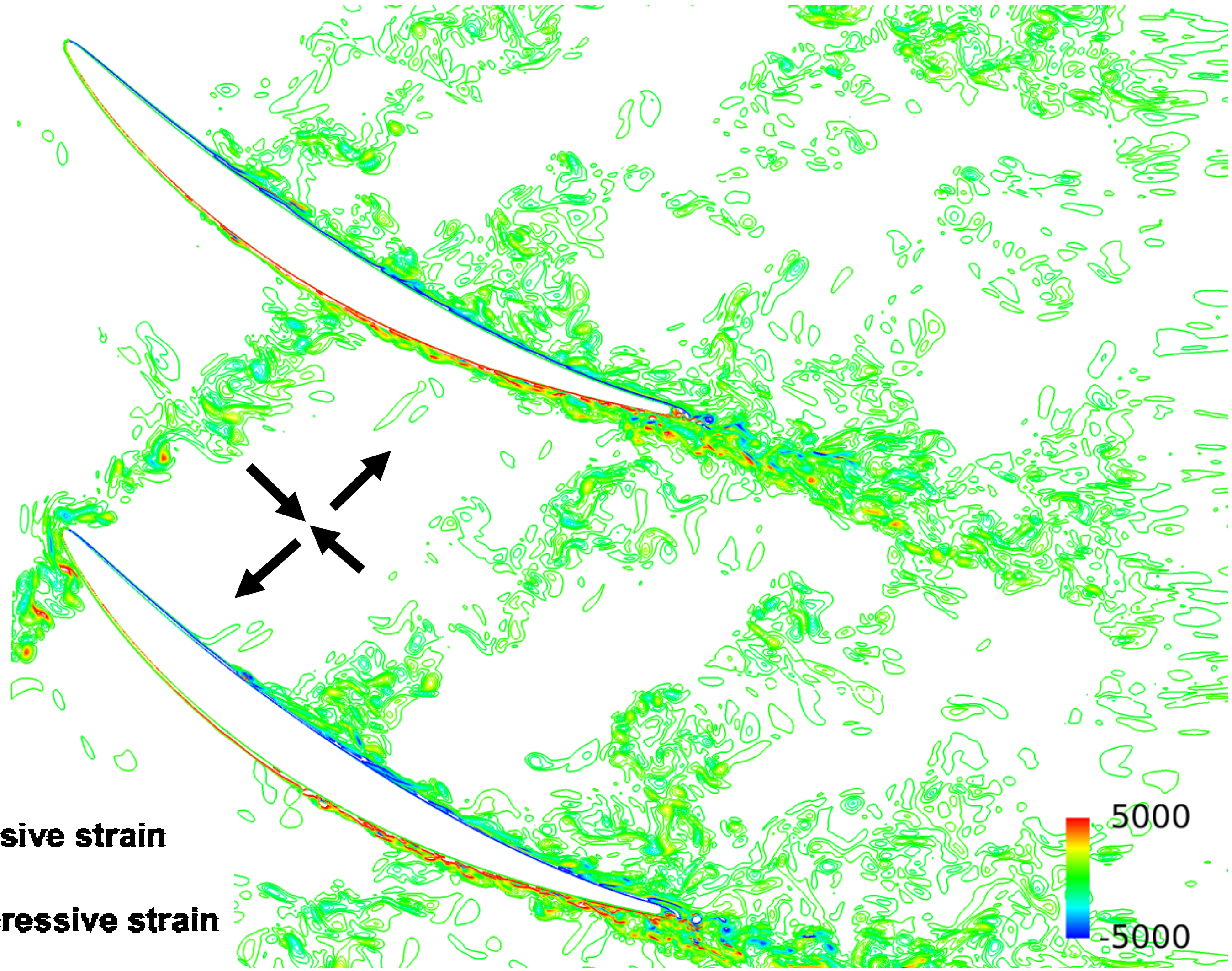
30% Span



50% Span

Flow physics of wake recovery

Local strain rate of rotor wake inside stator passage



extensive strain

compressive strain

Turbulence energy transfer through wake stretching

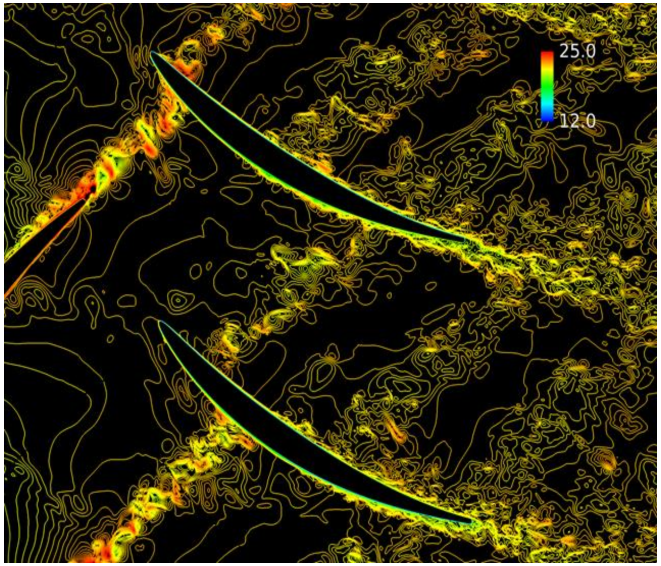
1. Turbulence energy production. (Soranna et al.[2006])

$$P_{ij} = -\overline{u_i' u_k'}\frac{\partial \overline{U_j}}{\partial x_k} - \overline{u_j' u_k'}\frac{\partial \overline{U_i}}{\partial x_k}$$

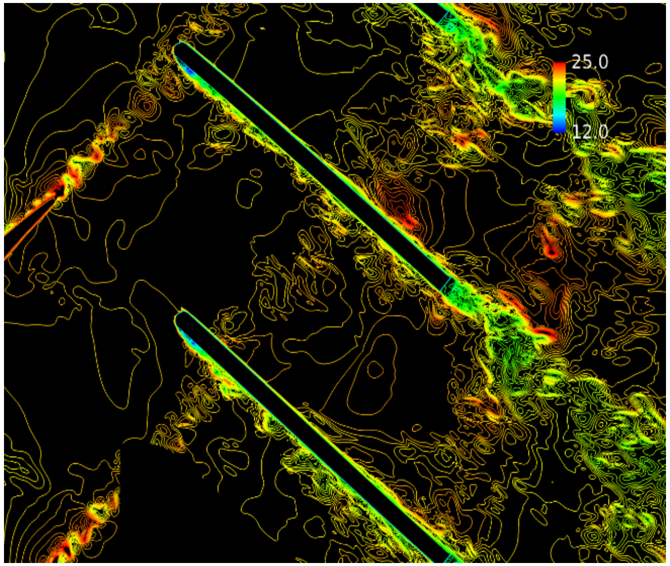
2. Wake stretching can transfer
energy to different frequency domain.

3. Phenomena of small eddy interaction.

No wake stretching in flat plate stators, Pt at 30% span, 29% spacing



Original stator blade



Flat plate blade

Concluding remarks

- 0.5 % Pt gain with the reduced spacing, 63 % is due to upstream pressure effect and 22 % is due to wake recovery.
- Wake recovery is due to energy transfer from turbulence to main flow. Turbulence production becomes negative due to opposing strains as wake stretches in non-equilibrium turbulence.
- Energy transfer occurs through small 3-D vorticities.